ON THE VORTICAL STRUCTURES IN A LINEAR BLADE CASCADE

E. Flídr 1, T.Jelínek 1, M. Němec 1
1 VZLÚ - Czech Aerospace Research Centre, Beranových 130, 199 05 Prague - Letňany, Czech Republic

Abstract

Paper deals with the investigation of the vortical structures in a linear blade cascade, more specifically this work is focused on the vortical structures in the end-wall region of the cascade. The effects of three different inlet flow angles ($\alpha_1 = -25^\circ; 5^\circ$ and $30^\circ$) were studied under the constant isentropic Mach number ($M_{2,is} = 0.4$) and Reynolds number ($Re_{2,is} = 4.5 \times 10^5$).

Keywords: Linear blade cascade, vortical structures, pressure measurement.

1 Introduction

The vortical structures in the linear blade cascade are complicated flow phenomena, that are not fully understood till these days. These vortices are affected by many parameters, e.g. flow turning in the blade cascade, Reynolds number, Mach number, etc. The evolution of the vortical structures in the flow channels and even in blade cascade was theoretically described by many authors, see e.g. [1, 2, 3, 4, 5, 6]. It can be concluded based on the analyses of these papers that with increasing curvature of the flow path, vorticity generated in the flow field will be stronger. Reynolds number will be responsible for the vortex diffusion, i.e. with higher Reynolds number vortices will be more concentrated along their axes. The geometry of the vortex (e.g. its pitch) will be affected by the acceleration of the flow within the cascade, therefore by the Mach number evolution.

Theoretical predictions were studied experimentally as well. The evolution of the end-wall flow with increasing distance from the trailing edges of the blade was investigated in [7], they focused on the local distribution of vorticity, velocity and kinetic energy dissipation as well as on the evaluation of integral values of pressure dissipation coefficient along the blade span. Their results confirmed predictions of the theoretical works and added observation about the significance of the trailing shed vorticity, which was not included in the theoretical research. The same methods of experimental investigations were used in [8, 9, 10], where off-design conditions of the cascades were studied. Even these papers confirmed the theoretical predictions.

Several models of vortical structures in the linear blade cascade were formulated based on theoretical and experimental research. One of the first models was a model proposed by in [1] based on the theoretical analysis, followed by the models developed based on experimental data. At first, the models were simple in [11, 12] and evolved into more complicated and precise in [13]. More details about the near-wall flows can be found in reviews [14, 15, 16]. Based on information obtained from these papers end wall flow model is depicted in Figure 1.

Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>Blade chord</td>
</tr>
<tr>
<td>$H$</td>
<td>Helicity</td>
</tr>
<tr>
<td>$M$</td>
<td>Mach number</td>
</tr>
<tr>
<td>$p$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$\mathcal{P}$</td>
<td>Vortex helix pitch</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>$r$</td>
<td>Reattachment line</td>
</tr>
<tr>
<td>$\mathcal{R}$</td>
<td>Reattachment point</td>
</tr>
<tr>
<td>$s$</td>
<td>Separation line</td>
</tr>
<tr>
<td>$\mathcal{S}$</td>
<td>Separation point</td>
</tr>
<tr>
<td>$t$</td>
<td>Cascade pitch</td>
</tr>
<tr>
<td>$u$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$x_i$</td>
<td>Components of position vector</td>
</tr>
<tr>
<td>$x$, $y$, $z$</td>
<td>Cartesian coordinates</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Inlet flow angle</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Vorticity</td>
</tr>
</tbody>
</table>

Indexes

$2,is$ Isentropic at the cascade outlet
$s$ Streamwise
The inlet boundary layer separates in the saddle point \( \mathcal{S}_1 \). Along the separation line \( s_{1,p} \) rolls up the pressure leg of the horseshoe vortex. This pressure leg is drawn into the blade channel due to the pressure gradient and is fed here by the low momentum fluid from the inlet boundary layer. This leg is, moreover, interacting with the cross-flow in the channel. Described mechanism is responsible for the formation of the so-called passage vortex, which separates along the separation line \( s_{2,p} \). The suction side of the horseshoe vortex moves along the suction side of the blade with its separation line \( s_{2,s} \). The separation lines \( s_3 \) and \( s_5 \) are connected with small corner vortices. All these vortices interact and occupy different positions at different distances from the trailing edges of the blades.

2 Aim of the work

This work is a continuation of the research of vortical structures in the linear blade cascade and follows the previous works, where the vortical structures were investigated qualitatively based on the surface flow visualization [17, 18]. The visualizations showed that with increasing inlet flow angle the vortical structures were more shifted toward the blade midspan. Increasing Reynolds number caused, that the vortices were less diffused and increasing Mach number resulted in the stretching of the vortices when the Mach number reach the value of 1, the shock wave was formed which interacted with these structures. From the unsteady point of view were these vortices investigated in [19, 20]. It was shown that there were three significant frequencies in the power...
spectra, that were not observed at the blade midspan, therefore they were connected with the interaction of the vortical structures in the end wall region. The effect of the vortical structure on the kinetic energy dissipation was investigated in [21], while the evolution of the static pressure distribution on the end wall under different inlet flow angles was studied in [22]. Results from both these works agreed well with the theory of flow in linear blade cascades. The variation of the Reynolds number affected mostly the dissipation of the kinetic energy at the blade midspan (enhanced Reynolds number decreased the dissipation) and increasing inlet flow angle increased the dissipation of the kinetic energy connected with end wall flows.

The aim of this work is to continue with the exploration of this phenomenon and obtain more information about the geometry of the vortices, that occupy the end wall region of the linear blade cascade. This will be performed by the calculation of the helicity and pitch of the vortical helix from the measured data at the cascade outlet. These parameters were not evaluated earlier.

3 Experimental apparatus, setup and methods

3.1 Apparatus

The experiments were conducted in the circular low-pressure aerodynamic wind tunnel in the VZLU laboratory of high-speed aerodynamics at Palmovka. The flow in the tunnel was driven by the twelve-stage radial compressor where the Mach number was set by the compressor’s rotational speed. The pressure in the tunnel was changed by the set of vacuum pumps, which resulted in a reduction of the air density and therefore in the variation of the Reynolds number. This tunnel construction allowed the independent variation of the Mach number and Reynolds number, respectively. The scheme of the wind tunnel is shown in Figure 2.

![Wind tunnel scheme.](image1)

The inlet flow angle was set by a pair of semi-shaped nozzles positioned in front of the cascade. The cascade was composed in the test section from the individual blades assembled between two acrylic wind tunnel windows.

The measurements were performed by the five-hole pyramid pressure probe at the cascade outlet. This probe with its dimensions and with definitions of the pressure taps is depicted in Figure 3.

![Five hole pyramid pressure probe.](image2)
3.2 Setup
Experiments were conducted under the constant both isentropic Mach number $M_{2,\text{is}} = 0.4$ and isentropic Reynolds number $Re_{2,\text{is}} = 4.5 \times 10^5$ for three different inlet flow angles $\alpha_1 = (-20^\circ; 5^\circ$ and $30^\circ)$. Measurements were performed across two cascade pitches $t$ with traversing step of 1 mm. The pitch to chord ratio of the cascade was $t/c = 0.6$ in this case. The traversing step along the $z$ axis was chosen with respect to the phenomena under investigation, i.e. the step was smaller in the near-wall region, where the occurrence of the vortical structures was expected and was wider at the cascade midspan, where the flow was considered as two-dimensional. Moreover, only one-half of the channel was measured due to the symmetry of the flow field with respect to the cascade mid-span.

3.3 Methods
Pressures measured by the pyramid five hole pressure probe were corrected by the calibration matrices, see e.g. [23]. The components of the velocity vector $u_i$ as well as its scalar $u$ were determined from these corrected pressures. The component of the vorticity in the $y$ direction was calculated directly from these velocity vector components as:

$$
\omega_y = \frac{u_x^{(i+1),j} - u_x^{(i-1),j}}{z^{(i+1),j} - z^{(i-1),j}} - \frac{u_z^{(i+1),j} - u_z^{(i-1),j}}{x^{(i+1),j} - x^{(i-1),j}}.
$$

(1)

Knowing the axial components of the vorticity and components of the velocity vector, other two vorticity components were established based on Crocco’s theorem, see e.g. [24]:

$$
\varepsilon_{ijk} u_j \omega_k = 1 \frac{\partial p_0}{\partial x_i},
$$

(2)

where $\varepsilon_{ijk}$ is Levi-Civita alternating symbol. The streamwise vorticity $\omega_s$ can be calculated as well. The flow was then locally described by the helicity density, which is defined as scalar product of the velocity vector and vorticity vector as:

$$
\mathcal{H} = u_i \omega_i.
$$

(3)

Several assumptions have to be made to calculate the pitch of the vortical helix. First, suppose that the velocity vector and vorticity vector were parallel. Second, it was assumed, that the flow was not accelerating nor decelerating behind the measurement plane, then the pitch of the vortical helix can be calculated as:

$$
P = \frac{4\pi \mathcal{H}}{\omega_s},
$$

(4)

where $\omega_s = \sqrt{\omega_i \omega_i}$.

3.4 Measurement chain and uncertainty
The flow regimes were set according to the measurement of state variables i.e. pressure (static and stagnation), and the temperature at the cascade inlet and outlet. The barometric pressure was measured by digital pressure transducer Druck DPI 145 with the uncertainty of 0.013% FS. The individual pressures were measured by the differential pressure transducers DRUCK with the uncertainty of 0.1% RDG. Temperature and relative humidity were both measured by the hygrometer Sensorika Humistar HTP-1 with the precision of $RH \pm 2\%$ and with the precision of $T \pm 0.3$ K. Mach number was set with uncertainty under 1% and Reynolds number with uncertainty under 2%. Flow velocity was measured with uncertainty under 6% and flow angles with uncertainty under $\pm 1.5^\circ$. The evaluation of the uncertainty was performed for the confidence level of 95% (standard deviation $\pm 2\sigma$).
4 Results and discussions

In Figure 4a - 4c the local distribution of the streamwise velocity is plotted under the different flow angles $\alpha_1$. The flow velocity reached values from $u_0 \approx 125 \text{ m} \cdot \text{s}^{-1}$ in the wakes and in the vortices centres up to $u_0 \approx 140 \text{ m} \cdot \text{s}^{-1}$ at the blade mid-span in the centre of the blade channel, where the kinetic energy dissipation of the flow did not occur. The regions of the lower velocities in the near-wall flow field were connected with the positions of the vortices in this region. There was only a whole passage vortex detected in the case of $\alpha_1 = -20^\circ$ (Figure 4a). Other vortices were shifted toward the blade midspan with increasing inlet flow angle and therefore more of them became visible in the case of $\alpha_1 = 5^\circ$ (Figure 4b).

Local distributions of the streamwise vorticity are shown in Figure 4d - 4f where the effect of the inlet flow angle is evident. The overall circulation in the blade channel was rising with increasing inlet flow angle and therefore the vortical structures in the cascade were more shifted toward the blade mid-span. In the case of $\alpha_1 = -20^\circ$ some vortices in the region close to the wall were not visible. This was given by the impossibility of measurements close to the wall (in the range of 0 - 6 mm) due to the dimension of the probe holder. The large counter-clockwise vortices were the passage vortices, while the smaller ones were suction side corner vortices and the clockwise vortices are pressure side corner vortices and the suction side leg of the horseshoe vortex. These vortices were interacting (wrapping) and, therefore, their positions in the flow field were dependent on the distance of the measurement plane behind the trailing edge of the blades.

The density helicity calculated according to eq. (3) is depicted in Figure 4g - 4i. It can be seen that the local distribution of this parameter copied the distribution of the streamwise vorticity in the flow field and is proportional to the helix pitch angle $\sin \beta$.

The main goal of this paper is to establish how many turns the vortex did in the blade cascade because the vortical models (and their figures) defined in the papers were often depicted with very large numbers of turns, but these images are highly inaccurate. The real situation can be observed in Figures 5a - 5c, where the local distribution of the vortical helix pitch is plotted with the distribution of the streamwise vorticity (black contour lines). Here the values, that were higher than 12 m were hidden. This was performed because, at the cascade centre, vortical structures did not occur, however, even there were small values of vorticity and therefore the ratio of $H/\omega_s^2$ was significant. From these figures can be deduced, that the one pitch of the vortex at the cascade outlet was in the order of 10 m. This result was valid for the assumptions mentioned in paragraph 3.3.

The results from the measurements of the inlet flow field, which will be discussed below will not be shown here, they were published in [21] and analysed in more detail in [25]. Based on these works, inlet flow velocity was evaluated as $u_1 \approx 24 \text{ m} \cdot \text{s}^{-1}$ for all studied cases, the inlet boundary layer was turbulent and its thickness was approximately $\delta = 1 \text{ cm}$. Considering outlet isentropic Mach number to be $M_{2,is} = 0.4$ that corresponds to $u_2 \approx 135 \text{ m} \cdot \text{s}^{-1}$ for the conditions in the tunnel an acceleration of flow in the cascade $u_2/u_1 \approx 5.6$ was reached. Assuming that the vorticity distributions were the same at the different positions in the cascade as at the cascade outlet and that only one parameter that was varied with this position was the velocity of the flow from $u_1 \approx 24 \text{ m} \cdot \text{s}^{-1}$ at the cascade inlet up to outlet velocity $u_2 \approx 135 \text{ m} \cdot \text{s}^{-1}$, then the vortex pitch can be estimated as $P \approx 2 \text{ m}$ at the cascade inlet. This value will be enlarging with increasing velocity in the cascade up to the mentioned 12 m at the cascade outlet. Note that this is very rough estimate due to the lack of data in the blade channel. However, based on this rough estimation, it can be concluded that in the tested cascade the vortices did not finish even one turn. From the work, [12] can be concluded, that in their case approximately one turn of the vortex in the cascade occurred. It must be noted, that in their case the flow velocity in the cascade was significantly lower ($u_2 \approx 2 \text{ m} \cdot \text{s}^{-1}$) and their blade chord were larger ($c = 0.12 \text{ m}$). The inlet flow field measurements will be used in the following work to establish these parameters more precisely in the following work. Then, the results obtained here will be confronted with more precise data.
Figure 4: Local distribution of streamwise flow velocity (a - c), streamwise vorticity (d - f) and helicity density (g - i).
5 Conclusion

The presented contribution deals with vortical structures in the linear blade cascade under different inlet flow angles. The effect of this parameter on the distribution of streamwise velocity, streamwise vorticity, helicity density and vortex pitch was investigated. It was shown, that the vortex pitch, in this case, was varied from the $P \approx 2$ m at the cascade inlet to $P \approx 12$ m at the cascade outlet. This conclusion tells us, that the figures in the papers about the vortical structures in the blade cascades are often inaccurate because the vortices are there depicted with several turns in the cascade, however, in reality, if the assumptions introduced here were correct, the vortex does not finish even one turn in the cascade. Inlet flow angle does not affect significantly this conclusion but affected the position of the vortical structures in the cascade (with increasing $\alpha_1$, vortices were shifted more toward the cascade midspan) in the manner that was predicted by the theoretical research.

The inlet flow field will be evaluated in more detail to obtain the data for more accurate evaluation of the parameters shown here in the future work. It will be useful as well to perform some numerical simulations to compare data from two different approaches.

References


\[ \text{Note, that the estimation of the inlet helix pitch was performed based on several rough assumptions that will not be completely correct and in reality this value will be smaller.} \]


